

## Long Term Stability in a Calibrated Time-Domain Network Analyzer

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### Abstract

We report on a fully calibrated digital sampling oscilloscope with time-domain reflection/transmission (TDR/T) capabilities. This system, known as a time-domain network analyzer (TDNA), calibrates Fourier-transformed TDR/T waveforms using a conventional network analyzer error model, and is used to measure the rf and microwave responses of devices and interconnects. While our TDNA measurements closely match data obtained with a commercial frequency-domain network analyzer (FDNA), we observe a difference in the TDNA results that increases with frequency. By comparing identical TDNA calibrations, we determine the upper bounds on the uncertainty due to the repeatability limits and show the overall accuracy of our TDNA system to be limited by the oscilloscope's ability to repeat measurements in the short term. Remarkably, this measurement uncertainty did not increase when making measurements as long as one week after the initial calibration.

### I. Introduction

While most oscilloscope calibration techniques focus on improving waveform recording in the time-domain, a number of researchers have demonstrated the application of frequency-domain correction algorithms to digital time-domain reflection/transmission (TDR/T) oscilloscopes [1-9]. With these approaches, a TDR/T oscilloscope is fully calibrated, similarly to the calibration of a conventional frequency-domain network analyzer (FDNA), and then used for rf and microwave device characterization. We reported in previous works [7-9] on the success of a direct application of the multiline TRL (thru-reflect-line) calibration to a time-domain network analyzer (TDNA) and have compared TDNA results to measurements made on commercial FDNAs. Though the agreement between TDNA and FDNA has been good, the TDNA data show an increasing scatter with frequency assumed to be associated with instrument repeatability limits. We report here on measurement repeatability in a calibrated TDNA system, and quantify the limits this places on the overall accuracy of vector network analysis results.

This paper begins with a review of our methods to calibrate TDR/T oscilloscopes and to obtain vector transmission and reflection coefficients ( $S$ -parameters) in the frequency domain. We provide example data for a number of calibrations and measurements up to 12 GHz, showing good agreement between our TDNA and a commercial FDNA system. Then, we describe a method of comparing two calibrations to determine an estimate of the repeatability error, and by examining the differences in  $S$ -parameters for two measurements of the same device, conclude that the oscilloscope's ability to repeat two measurements is mostly limited by short term (on the order of minutes) measurement uncertainty. Remarkably, we show this repeatability error does not increase significantly over the long term (periods of one week).

## II. Calibrated Time-Domain Network Analyzer

Our time-domain network analyzer system is depicted in Figure 1. It consists of a digital sampling oscilloscope (DSO) with TDR/T sample/source heads, a desktop computer, and software for acquisition and calibration. We use this system primarily for on-wafer device and interconnect characterization, making use of a microwave probe station. Consequently, the TDR/T heads are usually mounted on positioners directly behind wafer probes, and connected to the scope through extender cables. Semirigid coaxial cables connect the measurement ports to the probes, and the probes contact the standards and devices on wafer. A general purpose instrument bus (GPIB) connection provides data and control paths between the computer and oscilloscope.

Two NIST software packages<sup>1</sup> acquire and calibrate the data. The first program, TDNACal, initializes the oscilloscope, provides access to the relevant instrument controls, acquires the TDR/T waveforms, performs a fast Fourier transform (FFT), and saves both time-domain and frequency-domain records. Figure 2 shows the user interface to the TDNACal software. The current version of TDNACal also provides full two-port calibration using the OSLT (open-short-load-thru) technique. The second program, MultiCal®, is used to calibrate uncorrected FFT output using the multiline TRL method [10].

For typical measurements, we select instrument settings based on previous optimization studies [8], then configure the oscilloscope with TDNACal. We acquire data for a set of calibration standards and devices of interest using the same instrument configuration. By applying conventional vector network analyzer (VNA) error models, the software calculates the frequency-domain error coefficients from the standards data, and computes corrected frequency-domain  $S$ -parameters for each of the devices. Ideally, the calibration removes the frequency responses of the source, sampler, and all the cables and connections, providing an exact representation of the device response between the measurement reference plane. The results can either be used for frequency-domain network analysis directly, or to compute highly accurate time-domain responses through vector multiplication and inverse FFT techniques.

Since the TDNA calibration assumes perfect source and sampler repeatability, the source must faithfully reproduce the same voltage at the same time relative to the time base trigger throughout the measurements of all standards and devices. In practice this is not possible, but to approximate this condition, we enable an internal drift correction in the DSO [11] and reduce the measured drift to less than 0.5 ps over the period of our measurements. Even with this level of correction, the data shown below exhibit a level of random error in the frequency domain that exceeds that of commercial FDNA data.

## III. Measurements

This section provides example TDNA data from the process above, in comparison to calibrated FDNA measurements of the same devices. We have performed a number of complete TDNA calibrations and measurements and present four sets of data (A, B, C, and D); each letter represents a different calibration and measurement at various times over a two month period. All measurements were made with the same physical configuration and identical oscilloscope settings: number of points = 1024, window length = 10.24 ns, and number of averages = 256.

Figure 3 shows the magnitude of impedance  $|Z|$  for an on-wafer termination resistor for sets A-C (the resistor was not measured for set D), and Figure 4 shows the magnitude of the vector

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<sup>1</sup>These software packages are made available by NIST. Contact authors for information.

transmission coefficient  $|S_{21}|$  for a 20 mm long planar transmission line (delay time  $\approx 0.18$  ns) for all four sets. For both devices and all four calibrations, there is good agreement between TDNA and FDNA parameters over a broad frequency band.

In addition to device network parameters, MultiCal calculates the propagation constant of the transmission line standards at each frequency  $f$ . The propagation constant can be expressed in terms of a loss factor  $\alpha$  expressed in dB/cm, and the real part of an effective relative permittivity:  $\text{Re}\{\epsilon_{r\text{eff}}\} = [\beta c / (2\pi f)]^2$ , where  $\beta$  is the phase constant in radians per unit length and  $c$  is the speed of light. Figure 5 presents the loss factor as a function of frequency for NIST planar transmission line standards on a GaAs wafer, and Figure 6 gives the real part of the effective permittivity for the same lines. Again these data are compared to FDNA measurements of the same standards, showing excellent agreement well into the microwave region.

However, as seen in Figures 3-5, the TDNA data exhibit larger random scatter than the FDNA data, and in some of the data sets, small systematic offsets from the FDNA curves. In addition, two of the four TDNA calibrations give small offsets in the  $\epsilon_{r\text{eff}}$  as seen in Figure 6. Since the same standards and measurement procedures were used for all four TDNA data sets, it appears the accuracy of our TDNA data is limited by the instrument's ability to repeat measurements.

#### IV. System Repeatability

We applied the calibration comparison method [12, 13] to provide an estimate of the maximum differences one would expect between any two measurements of  $S_{ij}$  made over a specified length of time. Using the same calibrations and measurements described above (Sets A to D), we were able to make three comparisons for different periods between calibrations: one hour, one day, and one week. We took our first calibration as a reference and computed the two-port error model that would link this calibration to a second. Since the system remained nearly constant over the comparison period (one hour, day, or week), the error models linking two calibrations were used to compute the error bound based on system repeatability; that is, the maximum magnitude of the difference  $|S_{ij}^A - S_{ij}^B|$ , where A and B identify two measurements.

Figure 7 provides the repeatability bounds for the three different time periods studied for TDNA in comparison to a one-hour repeatability measurement we performed on a commercial VNA using the same standards. The maximum errors due to TDNA system repeatability are small and acceptable for many applications, but in comparison to FDNA results, TDNA repeatability errors are significantly larger. Remarkably, the week-long TDNA stability is comparable to the hour-long stability, indicating the source of error may be due to a short-term process alone.

To explore this further, we made multiple sequential measurements of a device without disturbing the contacting probes. Six sets of two-port data were collected in approximately 20 minutes, with less than one minute between measurements. We took five differences in  $S_{ij}$ , using the first of the six measurements as our reference. Figure 8 plots the maximum magnitude of the vector difference at each frequency in comparison to twice the repeatability bound. A factor of 2 is used here as a conservative estimate of the maximum uncertainty when subtracting or adding the two measured values. Though the difference curves generally lie below this conservative bound, they reveal a large short-term uncertainty that is isolated to waveform recording in the TDR/T oscilloscope.

## **V. Conclusions**

The results presented in this paper lead to a number of key conclusions regarding our time-domain network analyzer. First, by applying a complete network analyzer error model to a TDR/T oscilloscope, we can make device measurements up to microwave frequencies, at least for the passive test devices and interconnects considered here. All the example TDNA data sets collected over the long term follow identical trends and agree remarkably well with calibrated frequency-domain measurements of the same test devices.

In comparing calibrations that span three time periods (one hour, day, and week), we not only quantified a conservative uncertainty bound associated with system repeatability, but also demonstrated the long term stability of our TDNA system. Though the uncertainty bounds for our TDNA system are larger than the bounds of a conventional VNA, the TDNA data do not show significant differences in repeatability over one week. In other words, the stability of the TDNA system allows us to make a measurement one week after a calibration without significant increases in errors when compared to a measurement made one hour after a calibration. This is not what we observe for conventional frequency-domain network analyzers.

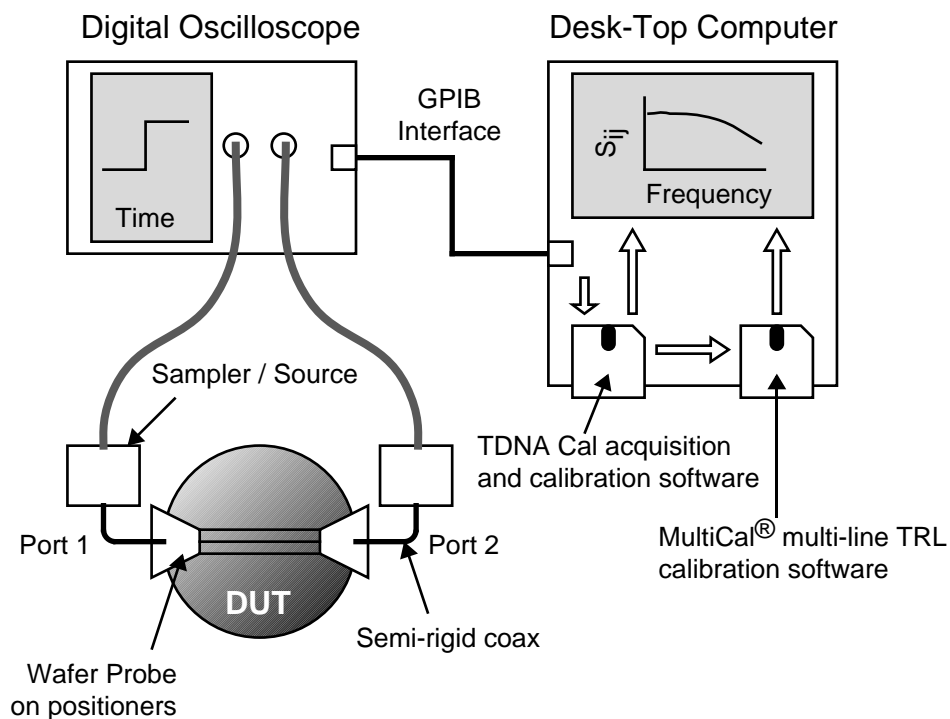
Finally, the comparison of multiple data sets collected from a single device without changes in probe position indicates a limit in the oscilloscope's ability to reproduce averaged waveforms over a time period of a few minutes. The residual drift in the waveforms we observe, even after enabling the internal drift correction of the scope, is a potential source of this repeatability error. Through other work in progress, we also know that subtle variations in sample jitter will effect the frequency-domain representation of a waveform; changes in jitter with time may also be a source of uncertainty in our system. Further work in this area will help identify and quantify the various sources of repeatability error, and may lead to additional correction techniques for calibrated time-domain network analyzers.

## **Acknowledgments**

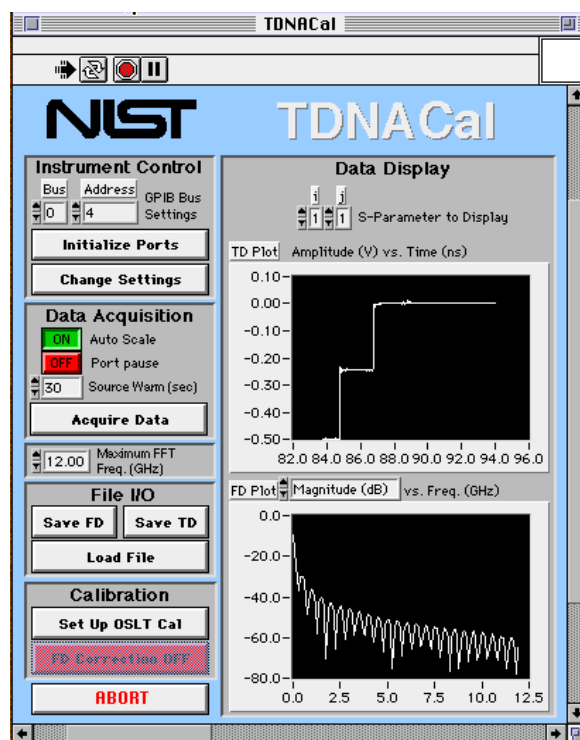
We thank Bong Seog Kil for his assistance in making a number of the measurements presented in this paper.

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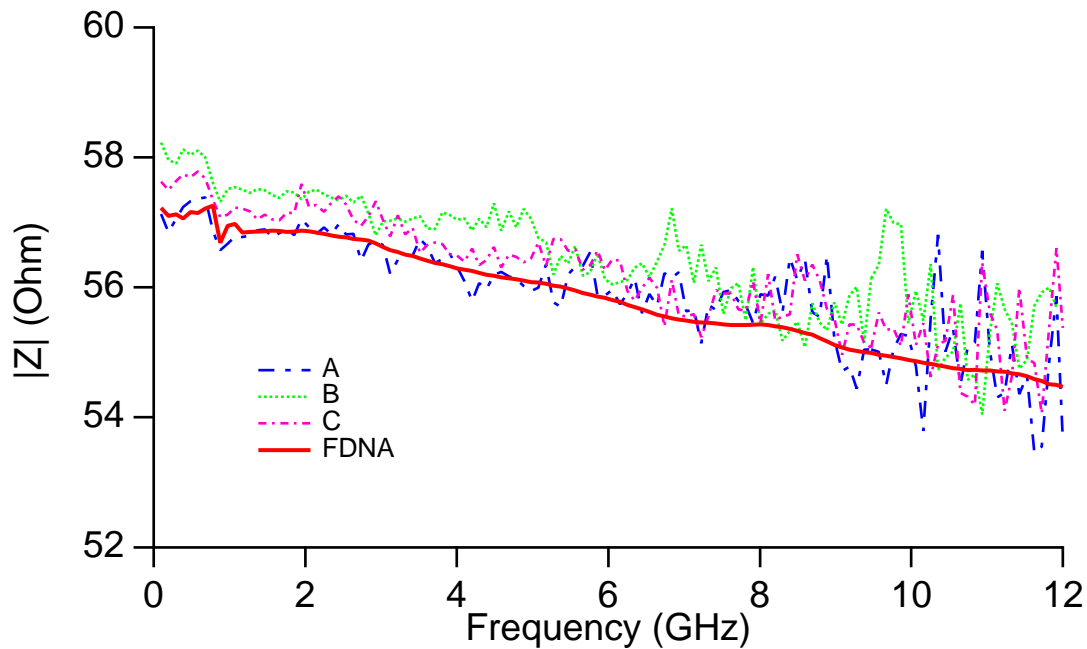
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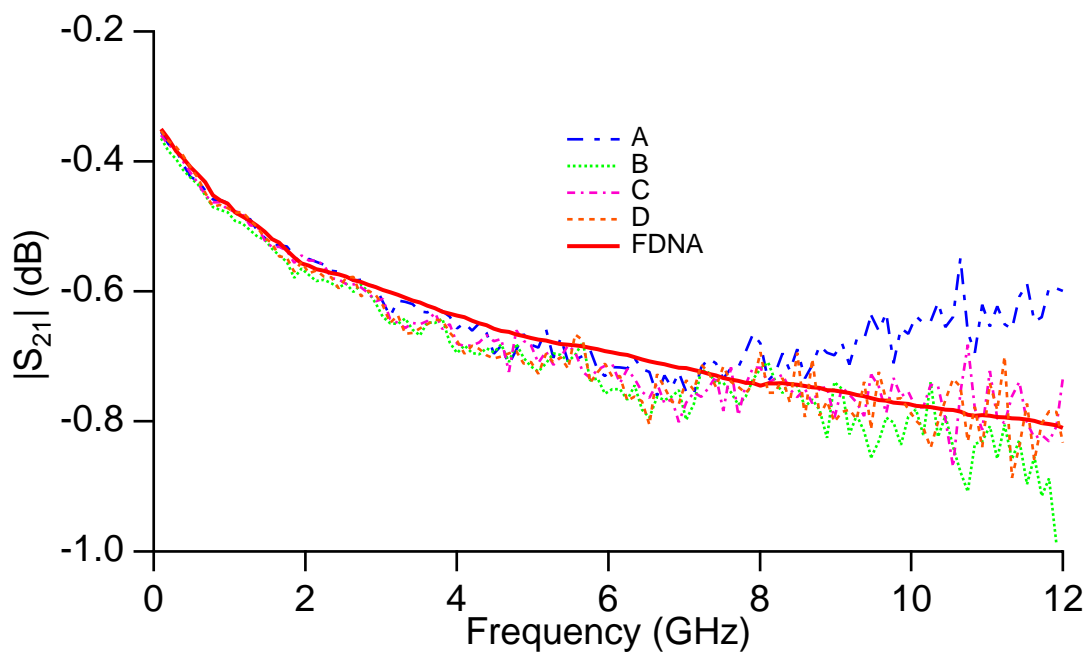
**Figure 1.** Block diagram of time-domain vector network analysis system used for probe station measurements.



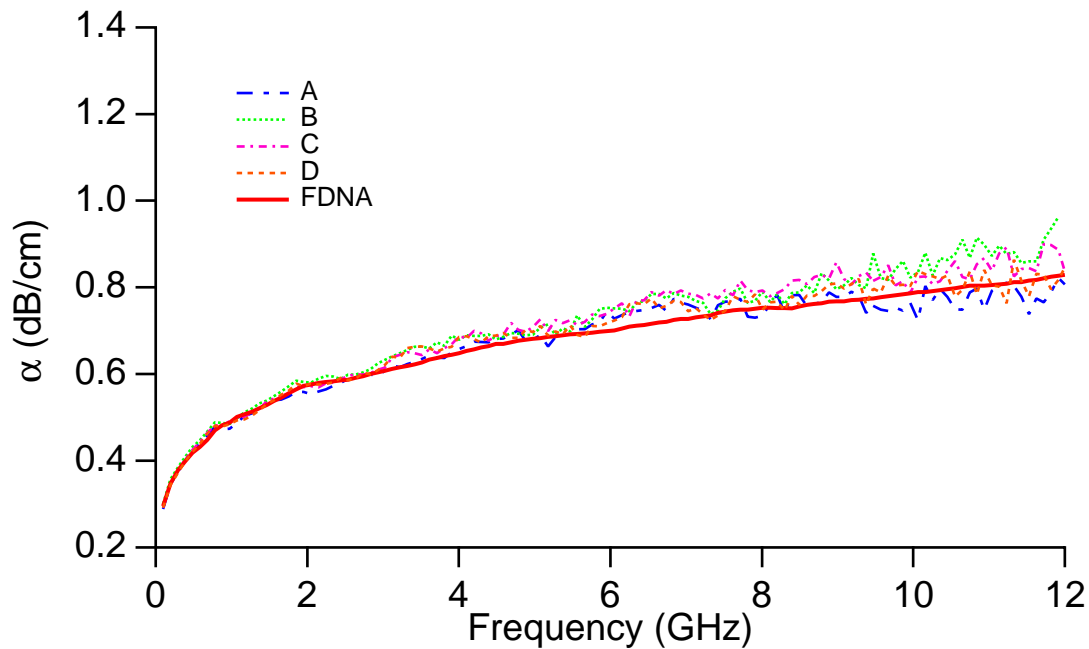
**Figure 2.** Screen capture of the main TDNACal control panel.



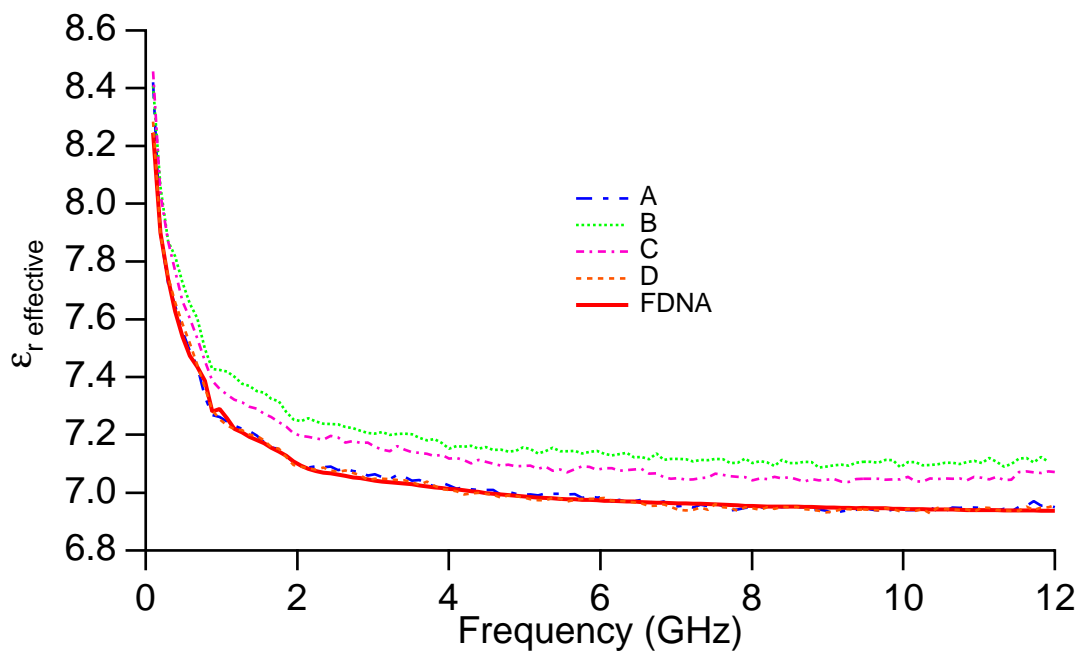
**Figure 3.** Frequency-dependent impedance ( $|Z|$ ) of an on-wafer termination resistor: Three TDNA measurements compared to a commercial FDNA system.



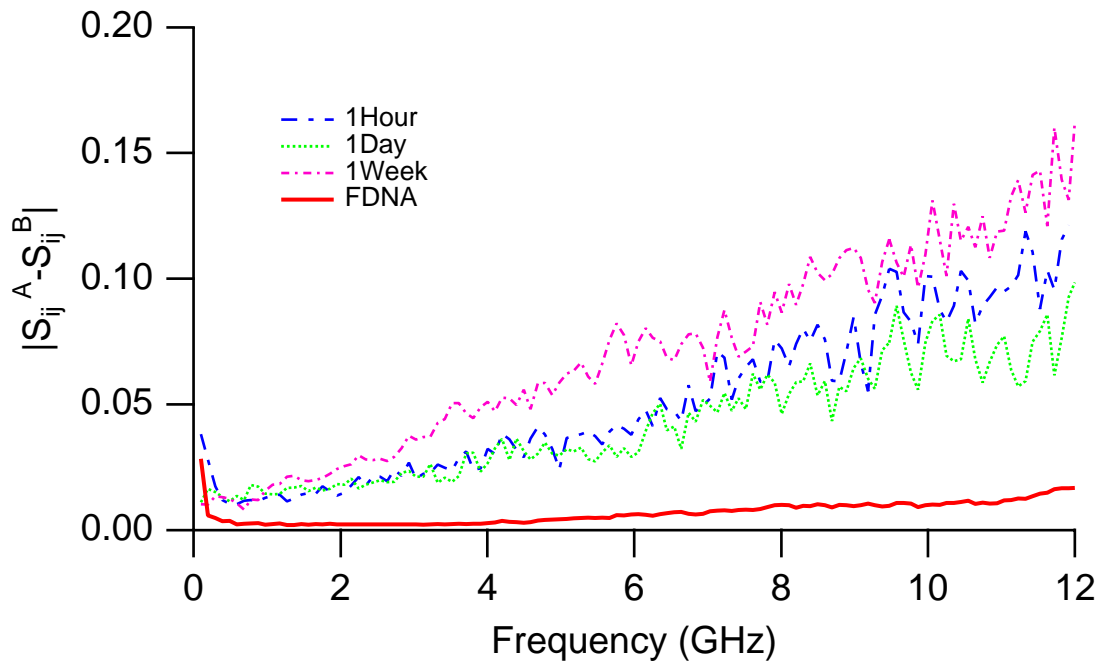
**Figure 4.** Frequency-dependent transmission coefficient ( $|S_{21}|$ ) of a planar transmission line: Four TDNA measurements compared to a commercial FDNA system.



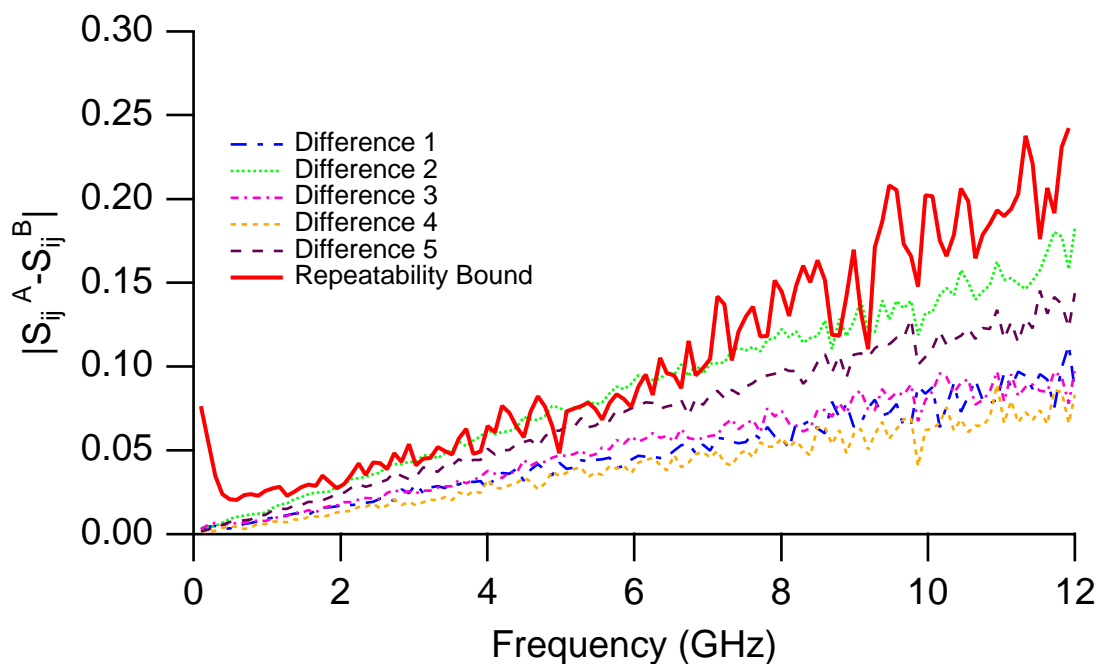
**Figure 5.** Loss factor of uniform planar transmission lines determined from a multiline TRL calibration: Four TDNA measurements compared to a commercial FDNA system.



**Figure 6.** The real part of the effective permittivity for uniform planar transmission lines determined with a multiline TRL calibration: Four TDNA measurements compared to a commercial FDNA system.



**Figure 7.** Measurement of repeatability in a TDNA oscilloscope using internal timebase drift correction: Measurements made one hour apart, one day apart, and one week apart. The solid line gives the one-hour repeatability of a commercial vector network analyzer for comparison.



**Figure 8.** Limits in TDNA oscilloscope repeatability. The maximum difference in  $S$ -parameters between measurements of the same device without breaking connections to the device: Five differences compared to worst-case repeatability bound.